Properties of Long-Unburned Duff Mounds in an Old-Growth Ponderosa Pine Stand

Implications for Restoration Burning

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Abstract

In fire-excluded old-growth forests, excessive duff consumption from smoldering combustion at the base of trees can result in injury and mortality. In this study, duff properties that influence consumption – mineral content, bulk density, and depth – were analyzed within and among duff mounds in a long-unburned ponderosa pine (*Pinus ponderosa* C. Lawson) stand. For each property, a substantial proportion of variance was attributable to differences among duff mounds and between upper and lower duff horizons (all $P < 0.05$), but no property differed between uphill and downhill sampling positions (all $P > 0.05$). A positive but weak relationship between tree size and duff depth was observed ($r^2 = 0.288$; $P < 0.0001$). Results can be used by fire managers to develop protocols for efficient and effective pre-burn duff mound sampling, in order to better protect large trees in old-growth stands from excessive duff consumption.

Keywords

Ecological Restoration; Old-Growth Forest; Pinus Ponderosa*; Prescribed Fire; Fire Ecology; Fire Effects; Klamath Mountains*

Introduction

Prolonged smoldering combustion and excessive consumption of duff mounds (accumulated fuels around the base of old trees) can produce mortality in North American *Pinus* forests following restoration burning (Ryan and Frandsen 1991, Swezy and Agee 1991, Varner *et al.* 2005, Hood 2010). Several measurable duff properties – moisture content, mineral content, and bulk density – have been identified as the primary determinants of the rate and amount of duff consumption (Frandsen 1987, Varner *et al.* 2005, Varner et al. 2009, O'Brien et al. 2010, Garlough and Keyes 2011). Aside from depth, relatively little is known about the variability of ponderosa pine (*Pinus ponderosa* C. Lawson) duff mound properties.

The likelihood of smoldering combustion occurrence decreases as duff properties cross threshold levels (Hartford 1989). Because mineral content absorbs heat that would otherwise contribute to combustion, the probability of ignition decreases as the ratio of mineral content to organic material increases (Hungerford *et al.* 1995). Higher bulk densities reduce oxygen concentrations and decrease the probability of independent burning at given moisture and mineral contents (Hartford 1989). Duff depth contributes to smoldering combustion via its relationship to moisture content: higher moisture contents require a greater minimum duff depth in order to initiate smoldering combustion (Miyanishi and Johnson 2002).

At northern California's Whiskeytown National Recreation Area (WNRA), old-growth relict stands are scarce and highly valued (Leonzo and Keyes 2010), and prescribed burning is considered a potentially valuable tool for their restoration and maintenance. With this study, we sought to help park resource managers optimize their pre-burn duff measurements in order to identify possible risks associated with prescribed burning. Duff properties (mineral content; bulk density; depth) were examined within and among mounds in a representative old-growth ponderosa pine stand at the WNRA. In a related experiment at the same study area (Garlough and Keyes 2011), moisture content was the primary determinant of duff consumption, but the properties analyzed here contributed significantly to consumption. Differences between the uphill and downhill sides of trees were anticipated, because accumulated litter tends to differ in thickness and composition. In addition, differences were expected in mineral content and bulk density between upper (Oe) and lower (Oa) duff horizons due to differences in their proximity to mineral soil horizons and their degrees of decomposition. Previous research (Ryan and Frandsen 1991) indicated a positive linear relationship between duff depth and tree diameter.

Methods

The study was conducted in an apparently long-unburned, old-growth stand at Whiskeytown National Recreation Area (WNRA) in the southeastern Klamath Mountains (40° 61′N, 122° 66′W). The stand occupies a 10-15% slope on a north-facing aspect ca. 250 m below the Shasta Bally summit, approximately 1650 m asl. Soils are well-developed and well-drained, derived from granitic/granodiorite parent materials (Fry and Stephens 2006). Average annual precipitation is approximately 105 cm (CDEC Brandy Creek Station, 40°61′N, 122°56′W). The stand consists of an overstory of ponderosa pine with a minor component of sugar pine (*Pinus lambertiana* Douglas), and a patchy understory of shrub tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehder var. *echinoides* (R. Br.) Abrams). Few trees in the stand showed any evidence of fire, which are believed to have last burned through the area in 1925 (Fry and Stephens 2006).

Study trees were chosen from a population with tree diameters at breast height (DBH) exceeding 50 cm (range 50 to 141 cm; mean 83 cm). DBH and duff depth at uphill and downhill positions were recorded for a total of 56 trees (112 samples total) during 23-29 October 2009. Upper duff (Oe) and lower duff (Oa) horizon depths were measured at 10 cm from the bole. From a subset of ten randomly-selected trees, 25 × 25 cm duff samples were removed from uphill and downhill positions. At the laboratory, samples were processed to determine duff bulk density and mineral content, separately for each position and duff horizon per tree. Bulk density (g cm^{-3}) was determined for each position and horizon from 10 × 10 cm subsamples, with volume calculated as average depth of the four sides, multiplied by the standardized length and width. Percent mineral content was calculated as the mineral (ash) proportion of duff oven-dry mass by placing the oven-dried shares of each sample in a muffle furnace at 450°C for 24 h.

A three-factor mixed model analysis of variance with random blocking was conducted to test for differences (in mineral content, bulk density, and depth; $\alpha = 0.05$) among duff mounds and between sample positions (uphill; downhill) and duff horizons (upper/Oe; lower/Oa), with all factor interactions tested. Sample position and duff horizon were fixed factors with two levels each, and individual duff mounds were random treatment blocks.

Results

Mineral content varied significantly among duff mounds (M) ($P = 0.040$) but was no different between uphill and downhill positions (P) ($P = 0.578$) (Table 1). Mineral content was substantially greater in lower horizons (H) (mean 34.7%) than upper horizons (mean 3.5%) ($P < 0.0001$) (Table 2), and more variable (range 6 to 65%) than upper horizons (range 2 to 8%) (Table 2). The position × horizon interaction term was non-significant ($P = 0.553$).

TABLE 1 ANALYSIS OF VARIANCE RESULTS FOR THREE DUFF PROPERTIES. P = POSITION; H = HORIZON; M = MOUND.

Factor	df	Sum of Squares	Mean Square	*F*	*P*
Mineral Content					
P	1	33.05	33.05	0.33	0.578
H	1	9716.31	9716.3	34.48	0.000
M	9	2975.63	330.63	3.44	0.040
P × H	1	36.52	36.52	0.38	0.553
Bulk Density					
P	1	0.0000	0.0000	0.00	0.950
H	1	0.0878	0.0878	9.50	0.013
M	9	0.0647	0.0072	2.99	0.059
P × H	1	0.0031	0.0031	1.31	0.282
Depth					
P	1	0.02	0.02	0.00	0.983
H	1	215.39	215.39	44.15	0.000
M	60	1076.28	17.94	8.17	0.000
P × H	1	1.29	1.29	0.59	0.446

TABLE 2 SUMMARY STATISTICS FOR THREE DUFF PROPERTIES, BY SAMPLE POSITION (UPHILL V. DOWNHILL) AND DUFF HORIZON (UPPER V. LOWER).

Property	Horizon	Position	Mean	Range	S.E.
Mineral Content %	Upper	Uphill	3.43	2.29-5.73	0.32
		Downhill	3.53	1.78-7.73	0.66
	Lower	Uphill	36.51	6.96-63.35	6.61
		Downhill	32.79	11.34-64.57	6.04
Bulk Density *g* cm^{-3}	Upper	Uphill	0.091	0.062-0.141	0.008
		Downhill	0.110	0.036-0.211	0.016
	Lower	Uphill	0.202	0.085-0.498	0.036
		Downhill	0.186	0.075-0.351	0.030
Depth *Cm*	Upper	Uphill	4.32	1-11	0.11
		Downhill	4.17	1-13	0.12
	Lower	Uphill	6.05	1-17	0.20
		Downhill	6.19	1-20	0.27

Duff bulk density (mean 0.147 g cm^{-3}) varied by horizon but was similar among mounds ($P = 0.059$) and between positions ($P = 0.950$). Bulk density of lower horizons (mean 0.194 g cm^{-3}) was nearly double that of upper horizons ($P = 0.013$, Table 1; mean 0.101 g cm^{-3}, Table 2). Like mineral content, variation in bulk density among lower duff (range 0.075 to 0.498 g cm^{-3}) was much greater than it was among upper duff (range 0.035 to 0.211 g cm^{-3}) (Table 2). The sample position × duff horizon interaction term was non-significant ($P = 0.282$).

Duff mound depths (upper and lower duff combined) averaged 10.4 cm (Table 2). Depth was linearly and positively ($P < 0.0001$), if weakly ($r^2 = 0.288$), related to

tree diameter (transformations did not improve fit). Depth did not differ between uphill and downhill sample positions (P = 0.983) (Table 1). Lower duff was 44% deeper (mean 6.12 cm) than upper duff (mean 4.25 cm) (P < 0.0001) (Table 2). The position × duff horizon interaction term was non-significant (P = 0.446).

Discussion

For duff combustion to be sustained, higher mineral contents must be offset by lower moisture contents (Frandsen 1987). Conversely, duff mounds of high mineral content possess lower moisture content thresholds at which restoration burning can be safely conducted. In experimental burning of duff from the same site, percent consumption was inversely related to moisture content for both duff horizons, and partially dependent on mineral content for lower duff (Garlough and Keyes 2011). In that study, an absolute no-burn threshold was identified for lower duff at mineral contents above 56 percent, and observed no-burn thresholds below 56 percent for combinations of mineral content and moisture content. For example, samples with mineral contents under 20 percent burned at moisture contents above 90 percent. Here, lower duff mineral contents averaged 34.7%, but at some mounds it exceeded 64%.

The combustion rate of duff increases with decreasing bulk density (Wein 1983), and higher bulk densities have been shown to lower the probability of ignition, especially at high moisture levels (Hartford 1989). Yet for this study's population, the range of bulk densities did not influence duff consumption (Garlough and Keyes 2011). Little is known about the variability of duff bulk density under field conditions, and it is often held constant in combustion experiments (0.10 g cm^{-3} is a commonly assigned to coniferous forests; Hungerford 1995). Our results showed that upper and lower duff horizons differ in their bulk densities, with the range of lower duff bulk densities notably broad (max = 0.4980 g cm^{-3}, mean = 0.1943 g cm^{-3}). This finding could explain manager-observed differences in consumption among mounds, and between upper and lower duff within mounds.

Conclusions

Information about variance within and among duff mounds can be applied by managers in pre-burn duff mound sampling strategies that minimize the risk of tree mortality by identifying when combustion threshold values have been crossed. Such conditions signal when mitigative measures to modify duff mounds are warranted. In order to capture the range of duff properties that exist, our findings have indicated that mineral content, bulk density and depth should be sampled from multiple trees; that sampling from both upper and lower duff horizons per mound is necessary; and that sampling from different positions (downhill, uphill) per mounds is unnecessary. Unlike moisture content, these properties can be sampled by managers at any time it is convenient to do so. Not all managers will be able to achieve such intensive pre-burn duff inventory and analysis. Yet for vitally important stands where losses associated with prescribed restoration burning are unacceptable (such as at the WNRA), our results have indicated how field efforts should be focused in order to efficiently and effectively characterize duff mound properties.

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